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Hypereutrophication of an Hawaiian Alpine Lake[1]

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ABSTRACT: A drought during the period 1977–1978 resulted in a roughly fourfold reduction in the volume of Lake Waiau, a small perched body of water near the summit of a volcano in Hawaii, and an over 200-fold increase in the late-summer chlorophyll *a* concentration. The normal planktonic flora of the lake was replaced during this time by an almost complete monoculture of the chlorophyte *Nannochloris bacillaris*. Nutrients required to support this bloom appear to have been supplied by an influx of interstitial water as a result of the development of an unusual hydrostatic head between the perched groundwater around the lake and lake surface water. The lake had not fully recovered from this episode 2 yr after termination of the drought.

LAKE WAIAU IS BELIEVED TO BE one of the highest alpine lakes in the United States. The lake has an area of 0.7 ha, an elevation of 3969 m, and is located in Waiau cone near the top of the dormant volcano Mauna Kea on the island of Hawaii (Maciolek 1969, EDAW 1975). When the lake overflows during the December and January period of maximum precipitation, lake depth is about 3 m. However, the lake gradually shoals during the summer due to seepage through the bottom and evaporation (Woodcock 1980), reaching an average minimum depth of about 2.5 m just prior to the return of the winter precipitation maximum. The water temperature is usually isothermal, and varies between 0° and 13°C (Woodcock 1980, Woodcock and Groves 1969).

The planktonic flora of the lake normally consists of a mixture of at least 11 species of diatoms and four species of chlorophytes (Massey 1978, Neal 1939). A mat of amorphous cyanophyta covers the bottom of the lake (Maciolek 1969). Beneath this mat is a layer of sediments from 1 m thick to over 7.5 m thick (Woodcock, Rubin, and Duce 1966). Carbon-14 dating of these sediments indicates that Lake Waiau is more than 9000 years old (Buckley and Willis 1969), and thus is probably of post-Pleistocene origin, an epoch when Mauna Kea was last glaciated (Gregory and Wentworth 1937). The phytoplankton population of the lake is characterized by a high standing crop but low primary productivity (Massey 1978). Diatom populations of $1.5–3.7 \times 10^9$ cells per liter and summer chlorophyll *a* (Chl *a*) concentrations of 6–30 mg m^{-3} have been reported in the lake (Massey 1978, Stefanick 1973). However, light-saturated productivity indices are only about 1.2–1.8 mgC mg^{-1} Chl *a* ha^{-1} (Massey 1978).

Precipitation, including snowfall at the nearby Mauna Kea Observatory, is highly seasonal, with maximum precipitation usually occurring in the November–March period. During the period July 1976 to November 1978, there was a statewide drought in Hawaii (Woodcock 1980), and the level of Lake Waiau dropped more than 2 m below its overflow stand. The severity of the drought in the Mauna Kea summit area is difficult to document due to the lack of an accurate record of solid precipitation, but in Honolulu, precipitation was about 46 percent below normal during 1977. Associated with this prolonged drought was a remarkable increase in the phytoplankton concentration in the lake and changes in species composition. The usual mixture of diatoms and chlorophytes was replaced by an almost pure monoculture

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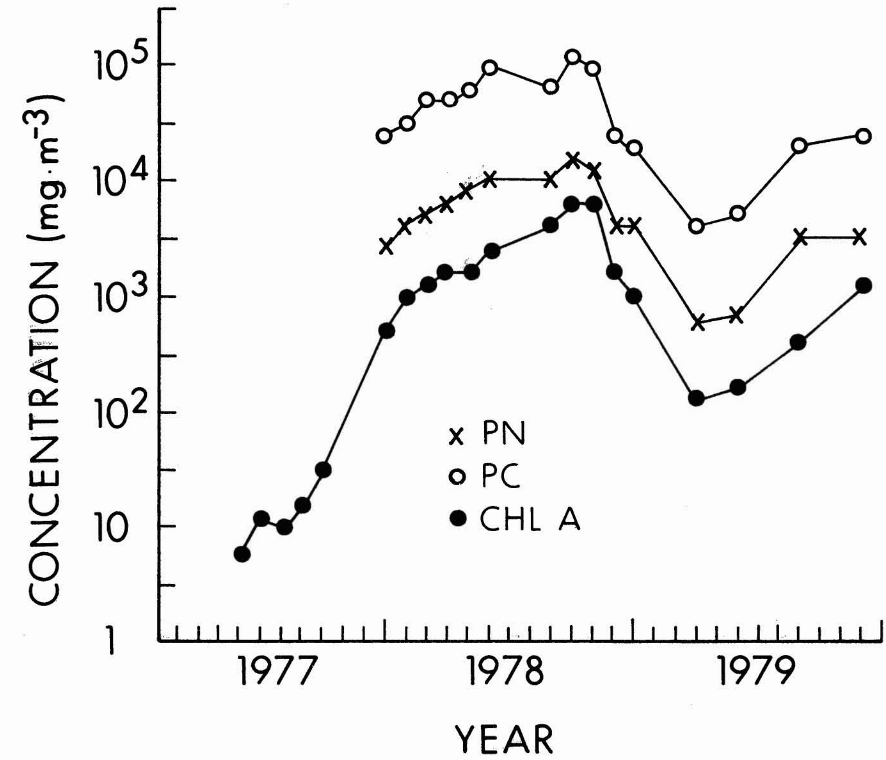

FIGURE 1. Concentrations of Chl *a*, particulate carbon (PC), and particulate nitrogen (PN) in Lake Waiau during the 1977–1979 period.

of the chlorophyte *Nannochloris bacillaris*. Chlorophyll *a* concentrations at the peak of eutrophication reached over 6.8 g m^{-3}, with concentrations of particulate carbon and particulate nitrogen reaching almost 11 mM and over 1.2 mM, respectively (Figure 1). The data reported here are the results of a lake sampling program conducted on roughly a monthly basis during the drought and for approximately 1 yr afterward.

MATERIALS AND METHODS

Water samples were obtained from a depth of a few centimeters at nearshore locations where the total depth of the water column was about 20 cm. Samples for particulate carbon and particulate nitrogen analyses were filtered onto GF/C glass fiber filters and stored frozen prior to analysis on a Hewlett-Packard model 185B CHN analyzer. Chlorophyll *a* samples were also filtered onto GF/C filters and were stored in methanol at −20°C prior to analysis on a Beckman Acta II spectrophotometer following precautions noted by Holm-Hansen and Riemann (1978). Nutrient analysis for ammonium and nitrate plus nitrite were made on lake water, groundwater, and sediment interstitial water following procedures given in Solórzano (1969) and Wood, Armstrong, and Richards (1967). A sediment core sample was taken from near the center of the lake in August 1978, using a 4-cm inside diameter glass tube, which was forced into the sediment by an operator in a small boat. The depth of the core penetration was about 0.5 m. Interstitial water was obtained by centrifuging samples of the core material, and filtering the supernatant. Sodium analyses were performed on lake water, groundwater, and interstitial water using a Perkin-Elmer model 603 atomic absorption spectrophotometer. Nitrogen-fixation rates were estimated using the acetylene reduction method following procedures outlined by Bohlool and Wiebe (1978). Lake volume estimates were made using monthly lake level measurements and the known bathymetry of the lake (Woodcock 1980).

RESULTS AND DISCUSSION

Monthly measurements of lake level during this time revealed that lake volume had gradually declined from about 11.6×10^3 m^3 in May 1977 to about 3.7×10^3 m^3 by March 1978, a factor of about 3.1. Analyses of groundwater samples on seven occasions during 1977 and 1978 revealed mean ($\pm$ standard error) sodium and inorganic nitrogen concentrations of 256 ± 13 μM and 38 ± 9 μM, respectively, with a mean N/Na ratio of 0.15 ± 0.04 by atoms. However, analyses of lake water during the peak of eutrophication revealed ratios of particulate plus inorganic N to Na as high as 1.0 by atoms, implying an enrichment of N relative to Na by a factor of roughly 6.7. Concentrations of Na in Lake Waiau at the peak of eutrophication in September and October 1978 were about 1.0 mM, an enrichment relative to groundwater by about a factor of 4. This increase in concentration could have been caused largely by evaporation of water from the lake during the drought, a conclusion consistent with the over threefold decline in lake volume from May 1977 to March 1978. However, the flow of water from Waihu Springs, which was fed almost entirely by seepage water from Lake Waiau during the drought (Woodcock 1980), was relatively constant during this time period, averaging about 30 m^3 day^{-1}. This rate of seepage alone could have accounted for about 86 percent of the reduction in the volume of the lake. In any case, the over thirtyfold increase in N (relative to groundwater) of Lake Waiau during the drought cannot be accounted for solely by evaporation.

Because of the remote location of Lake Waiau, contamination of the lake by human activities is almost certainly negligible. Estimates of nitrogen-fixation in the blue-green algal mat yielded nitrogen-fixation rates of about 0.34 gN $ha^{-1}day^{-1}$. This rate of nitrogen-fixation is about a factor of 200 smaller than the rate that would have been required to account for the increase of the nitrogen content of the lake during 1978, even if all the fixed N were made available to the water column community.

A more consistent explanation for the elevated N and Na concentrations in Lake Waiau can be made by examining the possible role of groundwater seepage into the lake. Under normal rainfall conditions, the lake surface level drops to no more than 25–30 cm below overflow level during the course of a year (Woodcock 1980). At a lake surface level of 26 cm below overflow, Woodcock and Groves (1969) reported that groundwater levels were about 10 cm above lake level at distances from 1 m to over 20 m from shore. During 1978, lake level dropped to about 180 cm below overflow, and measurements of groundwater level relative to lake level during that time at distances from 1 to 5 m from shore revealed an increasing hydrostatic head from 23 cm in January to 72 cm in October (Woodcock 1980: Fig. 7). Accurate calculations of groundwater seepage rates into the lake as a result of this head are difficult to make, because "it is seldom feasible to estimate permeability by less than an order of magnitude and because surface–groundwater interaction is often controlled at or very near the sediment–water interface" (Lee 1977). However, Lee (1977) has reported inflow seepage rates of about 17 cm day^{-1} at a hydraulic gradient of 0.1, and Woodcock's (1980) groundwater level measurements imply considerably larger hydraulic gradients (0.2–0.7) near the shoreline of Lake Waiau during 1978. Thus, we believe that the development of this gradient was undoubtedly adequate to force interstitial water up into the lake, at least in nearshore areas.

Concentrations of NH_4 relative to chloride

TABLE 1

CHLOROPHYLL *a* CONCENTRATIONS MEASURED IN LAKE WAIAU IN AUGUST 1977–1980

YEAR	CHL *a* ($mg\ m^{-3}$)
1977	17
1978	3800
1979	413
1980	280

have been reported to be as much as a factor of 5 higher in water seeping into lakes than in surrounding groundwater (Downing and Peterka 1978), presumably due to the decomposition of organic detritus in the upper layers of sediment. In the case of Lake Waiau, measurements of inorganic N and Na in interstitial water from a sediment core taken in August 1978 revealed N and Na concentrations of 90 μm and 0.7 mM. respectively, at a depth of 0.5 m, and 1.0 mM and 1.0 mM, respectively, at a depth of 10 cm. The 0.5-m values are about 2.5 times the corresponding groundwater mean values, with N and Na in nearly the same ratio; but the 10-cm values are almost identical to the N and Na concentrations found in the lake at the peak of eutrophication, and reflect an increase in the N/Na ratio relative to groundwater by a factor of 6.7, comparable to the enrichment of N relative to Cl noted by Downing and Peterka (1978).

Hypereutrophication of Lake Waiau therefore appears to have been caused by a two-step process: first, a lowering of lake level due to evaporation and seepage out of the lake from (probably) the central region of the lake, and second, an influx of high-nutrient interstitial water near the margins of the lake as a result of the development of a hydrostatic head of 20–70 cm caused by the lowering of lake level (Woodcock 1980). Presumably, some of this high-nutrient interstitial water was further concentrated by evaporation, but it is impossible without additional information to determine the relative importance of seepage and evaporation in eutrophicating the lake.

With the termination of the drought in 1978, phytoplankton biomass dropped dramatically (Figure 1), but a comparison of late-summer (August) Chl *a* concentrations during the period 1977–1980 (Table 1) shows that Chl *a* concentrations in 1979 and 1980 were still more than an order of magnitude higher than during predrought conditions, and the phytoplankton community during 1980 was still dominated by *Nannochloris bacillaris*. Complete recovery of Lake Waiau from this perturbation evidently will require more than a few years.

The natural eutrophication process is associated in part with a shallowing of limnetic systems due to the accumulation of sediments (Odum 1971). In the case of Lake Waiau, the accumulation of over 7.5 m of sediments on the bottom of the lake has undoubtedly contributed to the eutrophication process. However, the foregoing discussion indicates that periodic eutrophication of the lake now occurs by a different mechanism, namely by a shallowing of the lake during periods of low precipitation and a concomitant influx of nutrients from nearshore sediments. The steady buildup of Chl *a* concentrations during the summer while the lake level gradually drops (Figure 1) indicates that this process occurs on a seasonal basis. During periods of drought, the data presented here indicate that hypereutrophication of the lake may occur by the same mechanism. To our knowledge, Lake Waiau is the first example of a lake whose trophic status is changed regularly, and at times radically, by this mechanism.

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